by errors as large as about 10 waves. Figure 1 schematically depicts the apparatus used in an experiment to demonstrate such an application on a reduced scale involving a 30-cm-diameter aperture. The apparatus included a source of illumination at a wavelength of 1,064 nm; an object to be imaged (an illuminated dollar bill); two 30-cm amateur astronomical telescopes facing each other to emulate far-field imaging; a 19-element thermally actuated deformable mirror at the pupil plane of the receiving telescope; a Hartmann wavefront sensor; an image detector at the receiving-telescope focal plane; associated lenses, filters, beam splitters; and a flat mirror. The output of the wavefront sensor was processed, by a computer, to control signals for the thermal actuators on the deformable mirror. The lenses were chosen and arranged to reduce the diameter of the light beam to the widths of the deformable mirror and the wavefront sensor. The deformable mirror was placed at the pupil plane of the receiving telescope.

The various optics introduced aberrations characterized by, among other parameters, 1.4 wavelengths of root mean square (RMS) wavefront error. Then the closed-loop control system consisting of the wavefront sensor, computer, and deformable-mirror actuators was turned on, thereby reducing the aberrations (see Figure 2) to 0.05 wavelength RMS wavefront error. In addition, the Strehl ratio (the ratio between the peak intensity in the point spread function of an optical system and that of an equivalent diffraction-limited system) was increased from 0.08 percent to 89 percent.

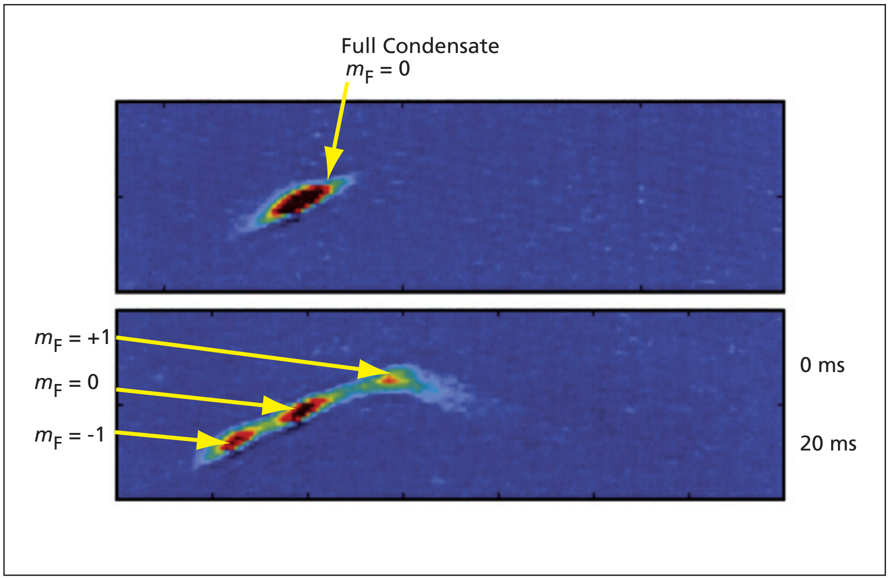
*This work was done by Hamid Hemmati and Yijian Chen of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-43173*

# Dual-Beam Atom Laser Driven by Spinor Dynamics

## A Bose-Einstein condensate is adiabatically compressed to drive coherent spin-mixing evolution.

*NASA's Jet Propulsion Laboratory, Pasadena, California*

An atom laser now undergoing development simultaneously generates two pulsed beams of correlated $^{87}$Rb atoms. (An atom laser is a source of atoms in beams characterized by coherent matter waves, analogous to a conventional laser, which is a source of coherent light waves.) The pumping mechanism of this atom laser is based on spinor dynamics in a Bose-Einstein condensate. By virtue of the angular-momentum conserving collisions that generate the two beams, the number of atoms in one beam is correlated with the number of atoms in the other beam. Such correlations are intimately linked to entanglement and squeezing in atomic ensembles, and atom lasers like this one could be used in exploring related aspects of Bose-Einstein condensates, and as components of future sensors relying on atom interferometry.




A **Bose-Einstein Condensate of $^{87}$Rb** atoms is shown at the instant of turning off the optical trap (0 ms) and at an instant 20 ms later. The original field depicted in these images measures 1 by 0.25 mm. Gravitation was directed toward the lower right; the trapping laser beam was aimed toward the upper right.

In this atom-laser apparatus, a Bose-Einstein condensate of about $2 \times 10^6$ $^{87}$Rb atoms at a temperature of about 120 μK is first formed through all-optical means in a relatively weak single-beam running-wave dipole trap that has been formed by focusing of a $CO_2$-laser beam. By a technique that is established in the art, the trap is loaded from an ultrahigh-vacuum magneto-optical trap that is, itself, loaded via a cold atomic beam from an upstream two-dimensional magneto-optical trap that resides in a rubidium-vapor cell that is differentially pumped from an adjoining vacuum chamber, wherein are performed scientific observations of the beams ultimately generated by the atom laser.

In the condensate as thus prepared, the atoms are in the magnetic-field-insensitive $m_F = 0$ sublevel of the F = 1 state [where F is the quantum number of total resultant angular momentum (electron spin plus nuclear spin plus electron orbital angular momentum) and $m_F$ is the quantum number of the component of total resultant angular momentum along a physically distinguishable coordinate axis (typically defined by a magnetic field)]. Then the intensity of the trapping laser beam is increased to drive coherent spin-mixing evolution: The increase in the intensity of the trapping laser beam adiabatically compresses the condensate to cause $^{87}$Rb atoms to collide and thereby to undergo the angular-momentum-conserving reaction

$$2(m_F = 0) \leftrightarrow (m_F = +1) + (m_F = -1).$$

As a result of this reaction, the original condensate becomes a superposition of (1) equal numbers of atoms in the $m_F$ = +1 and $m_F$ = –1 levels and (2) some other number of atoms in the initial $m_F = 0$ level.

Unlike the $m_F = 0$ level, the $m_F = +1$ and $m_F = -1$ levels are sensitive to an applied magnetic field. Therefore, several milliseconds before turning off the optical trap, a suitably oriented magnetic field having a gradient is turned on. By virtue of their different sensitivities to the magnetic field, atoms in the $m_F = +1$ level can be coupled out of the trap region in one direction and atoms in the $m_F = -1$ level in a different direction (see figure), thereby generating the desired two pulsed beams containing equal numbers of atoms. (The $m_F = 0$ atoms are affected only by the same gravitational force that affects the $m_F = +1$ and $m_F = -1$ atoms.)

*This work was done by Robert Thompson, Nathan Lundblad, Lute Maleki, and David Aveline of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).*
*NPO-43741*

# Rugged, Tunable Extended-Cavity Diode Laser

## This laser is relatively insensitive to vibration.

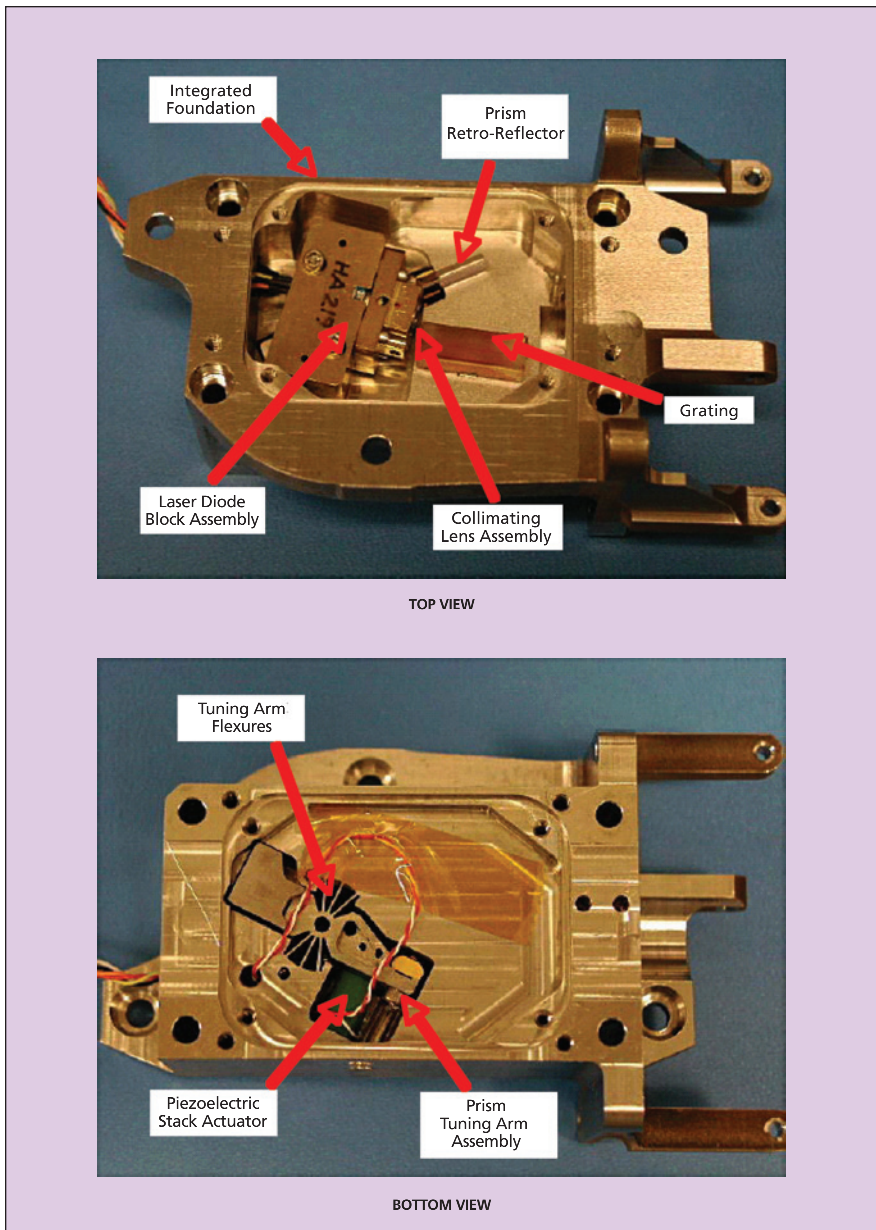
*NASA's Jet Propulsion Laboratory, Pasadena, California*

A rugged, tunable extended-cavity diode laser (ECDL) has been developed to satisfy stringent requirements for frequency stability, notably including low sensitivity to vibration. This laser is designed specifically for use in an atomic-clock experiment to be performed aboard the International Space Station (ISS). Lasers of similar design would be suitable for use in terrestrial laboratories engaged in atomic-clock and atomic-physics research.

Prior ECDLs, including commercially available ones that were considered for use in the original ISS application, were found to exhibit unacceptably high frequency noise in vibration tests. The high vibration sensitivity of those lasers was attributed to relatively low stiffness of tuning-arm mechanisms, characterized by fundamental-mode vibrational resonance frequencies of ≈2 kHz. In the design of the present ECDL, sensitivity to vibration is increased by increasing stiffness to a point characterized by a fundamental-mode vibrational resonance frequency >6 kHz.

The laser (see figure) includes a laser diode, an optical isolator at the laser output aperture, a collimating-lens assembly, a fixed grating, and a retroreflector prism on a pivoting tuning arm that is driven by a piezoelectric-stack actuator. The tuning arm pivots on flexure blades. The tuning arm and flexure blades are integral to an optical foundation made of Invar (a low-thermal-expansion iron-nickel alloy) and were formed by wire electrical-discharge machining of the foundation. The piezoelectric actuator is held in compressive preload by the flexure blades.

All of the aforementioned components except the flexure blades, tuning arm, and retroreflector are aligned and rigidly mounted within the Invar optical




In this **Tunable Extended-Cavity Diode Laser**, tuning is effected by piezoelectric actuation of the tuning arm, which pivots on the flexure blades.